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GUIDELINES FOR DESIGN OF UNDER-SEEPAGE CONTROL MEASURES FOR EARTH AND ROCKFILL DAMS

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GUIDELINES FOR DESIGN OF UNDER-SEEPAGE CONTROL MEASURES FOR EARTH AND ROCKFILL DAMS

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AMENDMENT NO. 1 OCTOBER 1988
TO
IS : 8414 - 1977 GUIDELINES FOR DESIGN OF UNDER-SEEPAGE CONTROL MEASURES FOR EARTH AND ROCKFILL DAMS

(*Page* 3, *clause* 0.2, *line* 5) — Add the word 'significantly' after the word 'quantities'.

(*Page* 5, *clause* 2.2 *line* 4) — Substitute 'an upstream blanket of impervious soil' *for* 'a blanket'.

(*Page* 6, *clause* 2.8) — Add the following matter after the third sentence:

'The diameter of ring bund should be large enough, that is, at least ten times the diameter of the boil, to avoid blow ups in the adjacent areas and its height should be sufficient to create enough head to reduce flow through boils.'

(*Page* 7, *clause* 3.1.2, *line* 3) — Substitute 'and' *for* 'end'.

(*Page* 8, *clause* 3.1.6, *last sentence*) — Substitute the following for the existing matter:

'Guidelines regarding this aspect are provided in IS : 8826 - 1978*.'

(*Page* 8, *foot-note*) — Add the following foot-note:

'*Guidelines for design of large earth and rockfill dams.'

(*Page* 9, *clause* 3.2.4, *last sentence*) — Delete.

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Indian Standard

GUIDELINES FOR DESIGN OF UNDER-SEEPAGE CONTROL MEASURES FOR EARTH AND ROCKFILL DAMS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 31 March 1977, after the draft finalized by the Foundation and Substructure Sectional Committee had been approved by the Civil Engineering Division Council.

0.2 Seepage control measures are required to protect a dam from any undesirable or dangerous effects of seepage, occurring through the dam itself or through the foundations, abutments and junctions with the masonry/concrete portions and outlet or spillway structures. The measures adopted may or may not reduce seepage quantities, but foremost, the measures should minimize the risk of failure from instability of slopes, from foundation heave or from piping by erosion or by a combination of these.

0.3 Although the control of seepage through and underneath embankments are treated separately, it should be realised that effective treatment of seepage requires consideration of the embankment, its foundation and the abutting or adjoining structures as a unit.

0.4 Internally, most earth and rockfill embankments require some form of seepage control, either to improve stability or to control piping or both and/or to reduce the quantum of seepage. In earth embankments, progressive zoning, horizontal drainage/filter mats inclined or vertical (chimney) drains and toe drains provide seepage control in the body of the dam.

0.5 The measures of under-seepage control to common usage are (a) positive cutoff formed in an open excavation to an impervious stratum which is backfilled with compacted impervious material, (b) concrete cutoff walls, (c) grout curtains, (d) slurry trench cutoffs (earth backfilled), (e) sheet piles, (f) upstream impervious blankets, and (g) vertical drains or relief wells and filter trenches. The measures best suited for any particular project depend upon many factors, but in general, the safety of the embankment shall be insured and, in addition, the type of treatment should be justified on the basis of economic considerations. In many instances, consideration of the various requirements leads to adoption of not one, but several types of seepage control measures.

0.6 Designing and detailing of the drainage system for the embankment should be closely co-ordinated with the designing and detailing of the under-seepage control system. Dimensions and layout of drainage gallery, vertical drainage trenches, drain holes and relief wells should be carefully dovetailed into corresponding features of the embankment to ensure the most positive control of seepage. Design and detailing of the core and impervious zones of the embankment should also be similarly coordinated with the arrangement and dimensions of the impervious elements of the under-seepage control system, such as cutoff trench, grout curtain, blanket, etc.

0.7 Certain aspects of under-seepage control measures are also covered by the following standards:

IS : 4999-1968 Recommendations for grouting of pervious soils

IS : 5050-1968 Code of practice for design, construction and maintenance of relief wells

IS : 6066-1971 Recommendations for pressure grouting of rock foundations in river valley projects

0.7.1 The following Indian Standards which are under preparation will also cover certain other aspects of the subject:

Code of practice for design of grout curtain and drainage systems in earth and rockfill dams

Code of practice for design and construction of diaphragm for under-seepage control

Guidelines for design of large earth and rockfill dams

0.8 In the formulation of this standard due weightage has been given to international co-ordination among the standards and practices prevailing in different countries in addition to relating it to the practices in the field in this country.

1. SCOPE

1.1 This standard covers the general guidelines for design of under-seepage control measures for earth and rockfill dams.

2. GENERAL PRINCIPLES FOR DESIGN OF UNDER-SEEPAGE CONTROL MEASURES

2.1 Provisions for seepage control have two independent functions: namely, reduction of the loss of water to an amount compatible with the purpose of the project, and elimination of the possibility of a failure of the structure by piping. Many dams have been in successful service for decades in spite of losses of water. Therefore the first step in rational design of seepage control measures is to estimate the largest quantity of water that may escape if no attempt is made to intercept percolation. In many instances it would be found that interception of the most conspicuously pervious zones would be sufficient and cost of further reducing the loss of water would not be justified in terms of value of water retained.

2.2 The quantity of seepage can be reduced by interception of pervious zones by means of impervious barriers, such as grout curtains, cutoff trenches, diaphragms or by lengthening the path of seepage by providing a blanket.

2.3 The safety of a dam with respect to a failure by piping is not necessarily related to the amount of water that escapes from the reservoir. Large losses of water may be associated with a high degree of safety against piping. Hence, the means for eliminating the danger of piping require independent consideration. The danger of failure of a dam by piping increases rapidly with increasing values of the hydraulic gradient at which the water percolates through the 'impervious' portion of the dam and along the contact between this portion and the natural ground.

2.4 Junction of earthfill with rigid structures, such as envelop junctions of earth and masonry dams, retaining wall junctions, intersection of outlet conduits and cutoff trench are particularly vulnerable to piping. Apart from the paths of preferential seepage provided by such junctions, cracking due to differential settlement is another major cause of internal erosion. Abutment contacts where the foundation profile is irregular and/or steep are also vulnerable to piping.

2.5 In certain cases piping can be prevented by providing properly designed relief wells and drainage trenches in conjunction with filter/drainage mats and inclined filters. If the subsoil is fairly homogeneous and well graded, the installation of these features is a routine operation. Entrainment of soil particles by seepage flows can be prevented without much difficulty by adopting accepted practices for dimensioning and detailing of the drainage system. However, if the subsoil contains strata of very fine uniform sand or rock flour overlying strata of clean sand or gravel subsurface, erosion may develop along the boundary between the two types of material. The most difficult and unfavourable conditions are encountered in ice or water-laid sediments having an erratic pattern of stratification and containing layers and lenses of very fine sand or rock flour in direct contact with coarse-grained and very pervious materials. Similarly vulnerable areas arise when hill talus and boulders occur in proximity of unconsolidated deposits.

2.6 Filter trenches in combination with inclined or vertical filters and horizontal filter mats constitute a means of arresting internal erosion. The filter trench, the horizontal drainage blanket as well as inclined and vertical filters through the embankment should be detailed carefully to constitute a continuous system for interception of possible paths of internal erosion.

2.7 Whatever the subsoil conditions may be, the means for prevention of piping should be fully and permanently adequate. Otherwise, sooner or later a catastrophic failure may ensue. Therefore, the efforts to stop subsurface erosion should be continued until they are successful. In some instances, observations during the first filling of the reservoir may show that minor additions to the original drainage provisions will satisfy all essential safety requirements. At other sites, on geologically similar formations, severe difficulties may be encountered.

2.8 If during filling of the reservoir occurrence of springs, boils and sediment entrainment is noticed corrective measures would have to be taken which generally consist of placement of a filter mat of well graded pervious material over the zones where excessive seepage is observed, followed by placement of a loading berm over the filter mat. Generally the material which can be most easily obtained and transported is used for the loading berm. Entrainment of particles and boils can be retarded temporarily by enclosing the boils by a ring bund of sand bags. Such ring bunds are a purely temporary measure and may often be helpful in creating suitable working condition for placement of the filter mat and the loading berm. When it is not possible to obtain material capable of satisfying the filter criteria as well as of adequately high permeability, gravel and rubble drains may be interposed within the filter mat or placed over the filter mat.

2.9 Control of seepage through pervious foundation is thus a feature of major uncertainty in the design of an earth dam. However, in many geological situations the depth of an extensive impervious stratum can be established by adopting simple methods of exploration, such as bore holes and trail pits. If depth of impervious stratum is not excessive a positive cutoff trench would be preferred in such cases. A positive cutoff trench formed in an open excavation into the impervious stratum and backfilled by a compacted impervious earthfill is comparatively free from uncertainty and requires little observation to ensure satisfactory performance.

2.10 When the depth of the impervious stratum is known but excavation of positive cutoff trench is not feasible due to excessive depth of the impervious stratum or construction difficulties like heavy dewatering requirements, instability of sides of excavation, etc, other measures of forming a cutoff may be considered. These consist of concrete cutoff walls placed in slurry trenches, grout curtains or sheet piles.

2.11 When the investigations do not provide definite indications of the depth and continuity of the impervious stratum or the depth of cutoff is excessive, consideration should be given to use of an impervious blanket. Blankets of adequate length in conjunction with relief wells or filter trenches have been successfully used on major projects. Adoption of a blanket-*cum*-relief well system imposes the obligation of maintaining continuous observation and exercising adequate control in installation of the drainage system. Inadequacies and uncertainties described in **3.6.3** on limitations of blankets should be considered before making the selection of the blanket as the primary measure of seepage control.

2.12 Partial cutoffs can only be considered as a supplementary means of seepage control since their efficacy is very small both for reducing the rate of seepage or for reducing the pore water pressure (uplift) in the downstream areas of the foundation. However, a partial cutoff in the form of grout curtain may be effective in blocking of zones vulnerable to internal erosion like pockets of open gravel and boulders in proximity of fine grained soil. Sheet pile may also be used as a means of blocking erosion in sandy and silty strata.

3. MEASURES OF UNDER-SEEPAGE CONTROL

3.1 Positive Cutoff Trench

3.1.1 The positive cutoff trench consists of an impervious fill placed in a trench formed by open excavation into an impervious stratum. Grouting of the contact zone of the fill and the underlying strata constitutes an integral part of the positive cutoff. Pockets of such size that compaction equipment cannot be operated and pot holes with overhangs should be filled with concrete.

3.1.2 The depth of the positive cutoff trench is governed by the geological features influencing the configuration of the impervious substratum and the profile of unweathered mass of bed rock. The width end side slopes are generally selected according to convenience of construction and to ensure stability of excavated slopes. Detailing of the positive cutoff near abutments and junctions with structures needs careful consideration, since the efficacy and continuity of the impervious filling (both in the cutoff trench and in the core) are compromised by differential settlement cracks developed near junctions, abutments and foundation irregularities.

3.1.3 In view of the hazard of transverse cracking and consequent internal erosion at junctions with rigid structures or next to steeply rising faces of abutments, an inclined or vertical filter should necessarily be incorporated in the embankment section for the junction zones irrespective of the need for such a filter on the embankment section for the entire dam. When combined with a filter trench provided in the junction zone, the inclined filter and the horizontal drainage blanket should constitute a complete and continuous interception system blocking all possible paths of internal erosion. The filter trench should be extended deep enough up to the upper surface of a foundation strata sufficiently resistant to internal erosion by virtue of its low compressibility, low permeability and cohesive strength.

3.1.4 Special attention should be given to backfilling of narrow trenches formed by excavation for the walls, outlet structures, masonry dams, etc. The contact of such backfill with the surrounding natural soil or rigid structure is likely to be poor due to the arching action arising from higher compressibility of the fill relative to the surrounding subsoil and the rigid structure. These difficulties can be overcome by use of plastic concrete backfill comprising coarse and fine aggregate, clay and a small quantity of cement.

3.1.5 Plastic concrete may also be used in narrow or deep trenches, excavated by manual labour where compaction equipment cannot be operated.

3.1.6 The cutoff trench should be keyed sufficiently into the flanks if the depth of pervious overburden below the reservoir level is significant at the ends of the dam at the flank. Guidelines regarding this aspect are provided in the draft 'Indian Standard Guidelines for design of large earth and rockfill dams (*under preparation*)'

3.2 Concrete Diaphragm

3.2.1 A single diaphragm or a double diaphragm may also be used for seepage control. Concrete cutoff walls placed in slurry trench are not subject to visual inspection during construction, therefore require special knowledge, equipment and skilled workmen to achieve a satisfactory construction.

3.2.2 Deformation behaviour of the diaphragm should be analyzed to ascertain the extent of risk of rupture of diaphragm due to upstream and down-stream horizontal movements combined with buckling due to down drag. Special design features would be necessary where such risk is serious, namely, replacing upper portions of the diaphragm by a positive cutoff trench, introduction of joints and use of plastic concrete.

3.2.3 By providing two lines of diaphragms and grouting the alluvium contained between them by tubes with sleeves, the element of uncertainty regarding the gaps and discontinuities in placement of concrete in slurry trench and defects in the joints can be minimized. Grouting of the pervious soil within the diaphragms could be carried out effectively because of the confinement provided by the diaphragms.

3.2.4 Limitations of the diaphragm technique can be overcome by installing precast elements within slurry trenches filled with plastic concrete. These improvements have, however, not yet been realized in India during actual execution.

3.3 Grout Curtain

3.3.1 *Grout Curtain in Pervious Soils*

3.3.1.1 Grouted cutoffs are produced by injection, within the zone assigned to the cutoff, of the voids of the sediments with cement, clay, chemicals, or a combination of these materials.

3.3.1.2 An essential feature of all grouting procedures is successive injection, of progressively finer pockets in the deposit. Inasmuch as grout cannot be made to penetrate the finer materials as long as more pervious pockets are available, the coarser materials are treated first, usually with the less expensive and thicker grouts, whereupon the finer portions are penetrated with less viscous fluids.

3.3.1.3 Grouted cutoffs are generally effective when seepage occurs primarily through pockets, zones or layers of coarse materials (gravel, boulders and talus). Coarse sediments with *in-situ* permeability of 10^{-1} cm/s or above and D_{10} exceeding 0·6 mm can generally be treated effectively with low cost grouts, namely, clay cement grout. The response of soils with permeability of the order of 10^{-2} cm/s and lower and D_{10} of 0·3 to 0·5 mm to grouting is uncertain. Silicate grouting has been effective in some cases for soils of initial permeability ranging from 10^{-2} to 10^{-3} cm/s. Close spacing of holes and expensive chemical grouts are required for grouting of soils of initial permeability of 10^{-3} cm/s and lower. Reference should be made to **5** of IS : 4999-1968* for assessment of groutability of foundation materials in terms of the grain size distribution.

3.3.1.4 For soil of initial permeability 10^{-1} cm/s or higher, the final coefficient of permeability of sediments grouted by use of low cost clay cement grouts lies in the range 10^{-4} to 10^{-5} cm/s. On the other hand the difference in pregrouting and postgrouting permeability of soils having an initial permeability of 10^{-3} cm/s would be insufficient for the cutoff to be effective. The width of curtain is another factor which shall be considered. Wide multiple line curtains would be required for soils of initial permeability of 10^{-2} cm/s, while a relatively narrow three line curtain may be adequate for soil of initial permeability of 10^{-1} cm/s or higher.

3.3.1.5 The sizes and locations of portions of the sediments not penetrated by the grout are unknown. Yet, if a layer of very fine untreated sand, for instance, crosses the grout curtain, water percolates through it at high gradients and may erode a gap. Most chemical grouts are extremely compressible; and some of them are vulnerable to leaching.

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*Recommendations for grouting of pervious soils.

Grout curtains with chemical grout which can withstand seepage pressure over a long period of time are relatively expensive and the grout materials are sometimes difficult to procure.

3.3.1.6 In the interest of safety and economy it is generally advisable to adopt multiple row grouting wherein the outer rows are treated with cement — clay — bentonite grouts, so that in the inner rows expensive grout treatment starting with stable grout mixes and ending in chemical mixes can be adopted which not only forms an effective grout curtain but also resist erosion and leaching.

3.3.1.7 The result of grouting operations also depends to a large extent on the skill and experience of the grouting personnel as well as the understanding and care with which supervision is carried out. The width of grout curtains should be adequate to contain stray pockets of fine sand which is not groutable and to ensure that the gradient across the grout curtain is low enough to ensure that the grout injected is not eroded or leached by seepage.

3.3.1.8 In view of the above limitations of grout curtains, it may be necessary to examine the need to provide a second line of defence, such as blanket plus relief wells. It may often be possible to obtain a blanketing effect by suitable adaption of the zoning of the dam near the base.

3.3.2 *Grout Curtain in Rock*

3.3.2.1 Grout curtain in rock admit of routinized treatment if the purpose is only to block the most pervious zones. These can be treated by cement grout with suitable admixtures.

3.3.2.2 Concentrated seepage would generally develop at the base of the positive cutoff. This zone is particularly vulnerable when a narrow base width is used for the cutoff trench in relation to the height of the dam. The depth of the grouted zone would be dependent on the nature of the substrata and their vulnerability to subsurface erosion.

3.3.2.3 In compact rocks with joints having percolation losses of the order of 100 lugeon or less or mass permeability of 10^{-3} cm/s, grouting is generally ineffective for control of pore pressures in the downstream part of the dam. In such cases drainage holes formed by continuation of the relief wells into rock or filter trenches excavated into pervious portions of the rock would be effective. Details of filter shall be carefully controlled in order to ensure satisfactory performance of the drainage system. The relief wells/drainage holes should be at accessible locations to admit of regular maintenance.

3.3.2.4 The extent of the zone requiring contact zone grouting depends on the vulnerability of the foundation material to internal erosion.

NOTE — The criteria for contact zone grouting are dealt with in a separate draft Indian Standard on design of grout curtains and contact zone grouting which is under preparation.

3.4 Slurry Trench Cutoff Walls

3.4.1 A backhoe or dragline excavates a trench through the pervious deposits down to suitable impervious materials. A bentonite slurry, retained in the trench above the existing ground-water level, prevents the trench walls from caving. After a sufficient length of trench has been excavated and the bottom suitably prepared, back filling begins. The physical characteristics of the backfill are specially controlled; in general, the backfill should be well-graded, impermeable in place, and sufficiently coarse to minimize postconstruction settlements. A selected amount of bentonite slurry may be blended with the backfill to improve its properties. The embankment should be suitably designed to resist cracking by differential settlement due to the slurry trench.

3.4.2 If the foundation materials are fine grained and overlie well-graded gravels, the hazards of piping are minimum. Piping may however occur into open work gravels. It may therefore be desirable to grout the alluvium in the immediate vicinity of the slurry trench. However, the slurry trench method is yet to be adopted in India and no Indian experience is available.

3.5 Steel Sheet Piles

3.5.1 Sheet piles are useful as barrier to arrest internal erosion. But they have proved to be rather ineffective as a positive means of controlling seepage through pervious deposits.

3.5.2 Even if sheet pile cutoffs are intact they are not water-tight because of leakage across the interlocks. In addition the locks may break because of defects in the steel or when a pile hits an obstacle. Once the lock is split, the width of the gap increases rapidly with increasing depth and may assume dimensions of a few metres.

3.5.3 If steel sheet piles are driven to hard rock with a very uneven surface, a continuous row of triangular gaps may be present between their lower edges and the rock, or the piles may curl if they are driven too hard.

3.5.4 It appears difficult to justify the use of sheet piling as a means of controlling seepage, particularly when other less expensive means are available which provide the same if not more positive results. Some methods may be perfected to improve the operating characteristics of sheet pile cutoffs, such as using vibrating pile driving hammers to reduce the probability of driving out of interlock and the use of bentonite mud to seal the interlocks; however, until such time that these techniques are perfected and become routine, sheet pile walls should be considered no more effective than partial cutoffs.

3.5.5 In barrages the efficacy of sheet piles is primarily due to their ability to prevent excessive exit gradients in down stream zones vuluner-able to scour. Sheet piles may also be effective in blocking the path of direct seepage at the contact of alluvium and rigid concrete floors of barrages. They also serve as an interception device against internal migration of soil particles.

3.6 Upstream Impervious Blankets and Relief Wells

3.6.1 *Upstream Impervious Blanket*

3.6.1.1 If a positive cutoff is not required, or is too costly, an upstream impervious blanket combined with relief wells in the down-stream section may be used. Filter trenches supplement relief wells in heterogeneous deposits and in zones of seepage concentrations. An upstream blanket may result in major project economies, particularly if the only alternative consists of deep grout curtains or concrete cutoff walls. Since alluvial deposits in river valleys are often overlain by a surface layer of relatively impervious soils, it is advantageous if this natural impervious blanket can be incorporated into the overall scheme of seepage control.

3.6.1.2 Feasibility studies for blankets should take into consideration the increase in the effectiveness of blankets with time as a result of additional sedimentation in the reservoir. Of course, this would be particularly important for dams across rivers which carry relatively large amount of sediment.

3.6.1.3 Following basic requirements should be satisfied while selecting the length and thickness of the blanket.

a) Reduction of the quantity of under-seepage to the desired extent.

b) Limiting the exit gradients to the allowable limits for the substrata encountered.

Subsurface erosion shall also be controlled which may require supplementary any measures in some cases.

3.6.1.4 The allowable seepage depends on economic considerations; therefore design decisions are governed by the estimate of seepage which is in turn dependent on the degree of precision achieved in determination of permeability. It is advisable to check the permeability values measur-ed in tests conducted in bore holes or on samples by large scale pumping tests with piezometric measurements.

3.6.1.5 Effective control of exit gradients can generally be achieved by a blanket length of about 5 times the head, combined with relief wells and drainage trenches. A longer length of blanket is generally required for control of subsurface erosion and for reducing seepage to desirable limits. It should, however, be noted that there is a limit to the length of the blanket beyond which it may not be useful.

3.6.1.6 Blanket length required to control subsurface erosion is a matter of considerable uncertainty. In uniform alluvial deposit without open gravel pockets or irregularities giving rise to paths of preferential seepage, blanket lengths of 10 times head have been found to be adequate. On important dams blanket lengths should be related to past practice under similar conditions and where possible provisions should be made for controlled filling of reservoir in stages. When past experience is inadequate or knowledge of geology indicates possible hazard of open zones in proximity with soils vulnerable to subsurface erosion, supplementary measures of seepage control shall be provided alongwith the blankets and relief wells. While selecting the length of the blanket the progressive reduction in efficacy of the increments to the blanket length especially when the blanket length is large relative to thickness should be considered.

3.6.2 *Relief Wells* (*See* IS : 5050-1968*) — Relief wells are an important adjunct to most of the preceding basic schemes for seepage control. They are used not only in nearly all cases with upstream impervious blankets, but also alongwith other schemes, to provide additional assurance that excess hydrostatic pressures do not develop in the downstream portion of the dam, which could lead to piping. They also reduce the quantity of uncontrolled seepage flowing downstream of the dam and, hence, they control to some extent the occurrence and/or discharge of springs. Relief wells should be extended deep enough into the foundation so that the effects of minor geological details on performance are minimized. It is necessary to note the importance of continuous observation and maintenance of relief wells, if they are essential to the overall system of seepage control.

3.6.3 *Limitation of Blankets and Relief Wells*

3.6.3.1 Sometimes unfavourable site conditions make it difficult and expensive to place the blanket properly, to ensure its continuity and to protect it from erosion. The following considerations would influence the blanket layout and costs:

a) Presence of a deep pool in the river requiring placement of blanket under water or dewatering of a large area after extensive coffer-damming operations.

b) River diversion layout and schedule requiring construction of blanket in sections. This makes it difficult to ensure satisfactory junctions of various sections of the blanket especially in the zone of intersection of the blanket with the diversion cut.

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*Code of practice for design, construction and maintenance of relief wells.

c) Unfavourable topography and geological features, such as abrupt steps in the hill sides, presence of talus and other pervious deposits of large extent on the abutment and flanks.

d) Possibility of erosion of the blanket by high velocity flow near entry and exit zones of the diversion cut or tunnel.

3.6.3.2 When blanket is considered as a measure of seepage control a complete layout plan should be prepared showing the outlet (including inlet and exit cuts) spillway approach and tail channels. The layout should be examined with regard to the ratio of shortest length of seepage path to the head, that is, the maximum overall gradient for the under seepage. Considerations should be given to addition of cutoff trenches to impervious bed rock near abutment flanks and junction zones. Supplementary measures, such as cutoff wall of concrete depending upon feasibility should be provided where efficacy of the blanket is liable to be compromised. Sheet piles may be used for protection of blanket in vulnerable areas.

3.6.3.3 Open gravel and talus deposits may cause paths of preferential seepage to be formed giving rise to sub-surface erosion. In such strata it may be impossible to prevent continuous and excessive discharge of silt into atleast some of the filter wells. Furthermore, while the reservoir is being filled for the first time, large springs discharging silt laden water may emerge downstream from the row of filter wells. Prevention of the silt discharge from such springs may require patient experimentation in the field because the pattern of seepage toward the springs is and will remain unknown regardless of the number of observation wells, inasmuch as the well records always leave a wide margin for interpretation. Difficulties also arise in installations and operation of relief wells if alternate layers of coarse and fine material exist.

3.6.3.4 If a filter stretching across the boundary of coarse and fine layers has everywhere the same composition, it is either too coarse to prevent the washing out of the fine particles or too fine to permit free discharge of the water out of the coarse stratum. If such a boundary or boundaries are encountered in filter wells, the lengths of the pervious sections of the wall of the wells should be limited to the central portion of the outcrops of the coarse grained strata. The thickness and elevation of the strata may change from well to well; therefore, a detailed record should be kept of the sequence of the strata that were encountered in each well while it was being drilled, and the specific procedures for the installation of each well shall be decided on the job.

3.6.3.5 The discharge from the relief wells may decrease with passage of time for one of several reasons: the reservoir may be silting up; the wells may be plugging with silt; or the well screens may be becoming obstructed by chemical deposits or products of corrosion. If the decrease in the discharge is due to silting of the reservoir, the water levels in the observation wells at full reservoir go down; in all other circumstances they go up. Excessive discharge of silt should be prevented by sealing off any silt layers or lenses during installation of the wells. Minor accumulations of silt should be flushed out periodically. For this reason, and to permit replacement of deteriorated screens, the heads of the wells should be readily accessible.

4. SELECTION OF SEEPAGE CONTROL MEASURES

4.1 The selection of seepage control measures is dependent on the nature of foundation strata, the degree of heterogeneity and uncertainty in foundation characteristics, the economic value of the water stored, the risk element as influenced by the height of the dam, reservoir volume and potential damage to important properties, lines of communication, and important towns. The choice of the seepage control system would also depend on the feasibility of testing the field performance by observations in the initial stages of construction or operation and the scope for taking corrective action before serious damage occurs. As seepage control is not amenable to routinization in design, the guidelines given are only an indication of preferred systems which have generally performed satisfactorily under similar conditions.

4.2 The most dependable measures of seepage control should be adopted commensurate with cost. Wherever feasible, a positive cutoff should therefore be used either in the form of a trench backfilled by compacted impervious soil or double line of diaphragm combined with grouting of the intervening soil or a multiple line grout curtain. Further, if depth of the impervious stratum is moderate and can be established with reasonable certainty, the choice would be a positive cutoff trench. Problems do, however, arise even in relatively simple geology (for example, igneous or metamorphic rocks or sedimentary rocks with thick beds) due to faults, shear zone dykes and similar discontinuities. These would require extensive grouting treatment beyond the zone intercepted by the cutoff.

4.3 When deep and extensive but fairly uniform pervious strata of permeability ranging between 10^{-3} to 10^{-1} cm/s are encountered, blankets combined with relief wells and drainage trenches have often been found to be adequate. Problems however, arise due to presence of open gravel pockets, zones of talus slide areas, contacts of formations of different geological age, folds, faults and fractured zones. Such features would call for supplementary measures, such as partial cutoff formed by a grout curtain. When permeability of the overburden is of the order of 10^{-3} cm/s or less, the quantity of seepage would be small and blankets of moderate length (about 5 times the head) would be adequate. However, such materials can be vulnerable to internal erosion. Close observation would therefore be required over a prolonged period since erosion channels are known to have developed 20 years or more after construction. Such cases call for continuous monitoring and evaluation of the performance of the seepage control system. Supplementary grouting treatment may be necessary initially or as a corrective measure.

4.4 When permeability is high, that is, of the order of 10^{-1} cm/s or higher, recourse to grout curtains and diaphragms is generally necessary. Grouting can be economical in such cases except where problems arise due to presence of boulders, blocks and talus with irregular rock profile which make it difficult to establish the depth of the curtain. Presence of pockets of material of permeability of the order of 10^{-3} cm/s embedded in the highly pervious mass would compromise the efficacy of treatment by grouting and untreated pockets may be vulnerable to internal erosion. In such cases blankets may have to be combined with grout curtain. Diaphragms would generally be preferred when such pockets of fine sand and silt are extensive and the average permeability is 10^{-2} cm/s or lower provided boulders do not make trenching operation impractical.

4.5 When the irregularities and heterogeneities are extensive, it is advisable to plan for checking of the performance of the seepage control system at various stages of filling of the reservoir. At the design stage consideration may be given to provide features that would help in raising the reservoir level in stages and control rise of water level until the performance of the seepage control system is verified and corrective action is taken, wherever required. This may entail introduction of special features in the spillway and outlet structures. Where controlled filling on the basis of observations is not possible, the under seepage design features shall be positive. All these should be considered to be a part of the design for seepage control. On projects where the risk of failure is high due to the large height of the dam and capacity of the reservoir, and existence of important properties downstream or the geological conditions are subject to a high degree of uncertainty, the designer should make the worst assumptions compatible to the geological conditions it may have also to be assumed that the worst condition would be developed during construction. Depending on the degree of uncertainty and the element of risk a second or sometimes a third line of defence may have to be used. This aspect has been further elaborated under **4.6**.

4.6 Combination of Measures to Provide Multiple Lines of Defence

4.6.1 An element of uncertainty always exists in respect of under-seepage control for earth dams except where geology and topography exclude the possibility of unfavourable local features, for example where a positive cutoff is provided up to compact and impervious bedrock and the cutoff extends sufficiently into the flanks. When a positive cutoff is not feasible from a cost and construction point of view or due to presence of geological discontinuities a second or third line of defence may be required.

4.6.2 Relief wells could be valuable adjunct to a seepage-control system comprising impervious blanket, filter mat and toe drains. A partial cutoff could also be used with advantage to intercept an upper stratum of relatively high permeability especially if the upper stratum contains open gravel, boulders, and tulus in proximity of fine sand and silt. A grout curtain of sufficient width may also constitute a partial cutoff where the alluvium is deep and contains pockets of fine sand which are not amenable to grouting. The grout curtain would then be used in conjunction with a blanket and relief well system. In such cases the grout curtain would be designed to block the most pervious zones rather than provide a compact cutoff.

4.6.3 In this standard, the term partial cutoff is used for imperfect curtains as well as cutoffs penetrating only a part of the depth of the principal pervious stratum. It should be recognized that a partial cutoff will generally bring about only a small reduction in the quantity of seepage and hydrostatic pressures in areas downstream of the curtain may not be lowered significantly. A partial cutoff is essentially a supplementary measure of control. For example, in a seepage control system consisting of blanket plus relief wells, if doubt arises regarding the presence of soil vulnerable to internal erosion in contact with open gravel pockets, partial cutoff formed by a grout curtain may be helpful in blocking such critical areas. A partial cutoff may also be helpful in intercepting zones of cracks and fissures existing up to a shallow depth in the foundation soils.

4.6.4 Deep drainage trenches filled with filter materials may constitute a second line of defence in conjunction with relief wells if it is apprehended that relief wells may not intercept all the probable paths of preferential seepage.

4.6.5 Grouting between concrete diaphragm walls or in the vicinity of slurry trenches would also constitute a second line of defence.

4.6.6 The necessity for a second or third line of defence would be decided on considerations of safety when the reservoir is large and also in view of the degree of uncertainty in design as determined by the geology as well as inherent limitations of techniques of exploration and construction.

4.7 Dependability of performance should take precedence over cost considerations for major dams. When the choice is made on grounds of economy possible variations from preliminary estimates should be given due consideration. Large variations may occur in estimates of diaphragms in respect of cost of chiselling through boulders and obstructions and in grout curtains in respect of spacing of grout holes, number of grout rows and grout consumption. The construction schedule for coffer dam, river diversions and dewatering should also be critically reviewed before opting for the positive cutoff trench.

5. EVALUATION OF CUTOFF EFFICIENCY

5.1 When there is no hazard of subsurface erosion, cutoff efficiency can be judged in terms of the reduction in the quantity of seepage. In practice, however, reduction of excess hydrostatic pressures in the downstream part of the foundation would be an important consideration. Therefore cutoff efficiency would best be judged in terms of hydraulic gradients obtaining in the downstream part of the foundation as well as the head loss across the curtain, as compared to the total reservoir head. For reliable evaluation of cutoff efficiency it is necessary to examine the downstream gradient by installing atleast two lines of piezometers downstream of the cutoff and the upstream gradient would be established by minimum of one line of piezometer. The upstream piezometer line should be placed as close to the cutoff as possible while avoiding the risk of blockage by grouting. Study of the reservoir level in relation to the upstream piezometer would serve to isolate the effect of natural blanket or artificial blankets. Alongwith a study of seepage gradients across the dam and its foundation groundwater contours before and after filling of the dam and during various stages to filling should be examined. Reliable interpretation of piezometric data and groundwater contours requires considerable study as the water surface contours reflect the combined effect of seepage flows across the dam and general seepage phenomena governed by the topographical and geo-hydrological features of the dam site.

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